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A method of identifying charged particles

By B. Forkman and S. A. E. Johansson

With 5 figures in the text

SUMMARY

A method for identifying charged particles is described. It consists of a combination of a magnetic field and nuclear emulsions. The orientation and length of the tracks in the emulsions are measured and the trajectories of the particles in the magnetic field are calculated, assuming them to be protons, deuterons, or α-particles. The intersection point relative to the position of the target in the various cases makes it possible to identify the particles. The method has been used successfully in an investigation of the charged particles emitted in photonuclear reactions.

Introduction

Determination of the mass of particles emitted in various nuclear reactions is an important problem. There exists a great number of methods and the choice depends on the type of the experiment. We will here be interested in the case of fairly low energies (1–10 MeV) and of low intensities. In this special case it is difficult to find a suitable method. If the intensity is low it is not possible to use conventional heavy particle spectrographs. Counter telescopes are difficult to use below about 10 MeV. Furthermore they are disturbed if the intensity of the background radiation is too high. A possible method is the use of a cloud chamber in a magnetic field [1, 2]. The simultaneous determination of range and curvature of the tracks gives the mass of the particles. This method is tedious and has a very low efficiency. It has therefore found only a limited use. Another possibility is grain counting in nuclear emulsions. It has been claimed that it is possible to separate protons from deuterons also when the particles are of low energy [3, 4]. More recent works show, however, that a complete separation is difficult to achieve in this way [5, 6].

We have developed a method, which has been successfully used for separation of protons, deuterons, and α-particles emitted in photonuclear reactions. The method consists of a combination of nuclear emulsions and a magnetic field. The length and orientation of the tracks are measured. The trajectory of each particle is then calculated assuming it is either a proton, a deuteron, or an α-particle. The intersections of the trajectories with the plane of the target give information as to what kind the particle is.

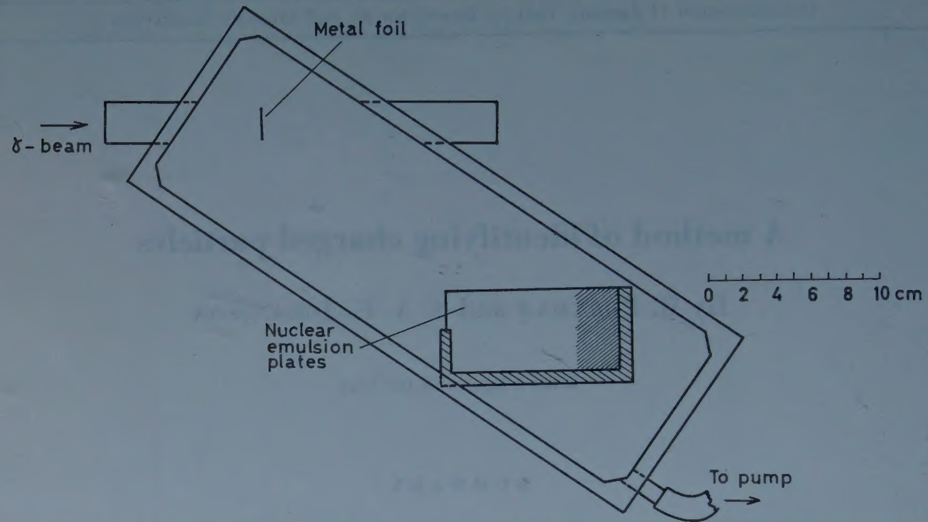

Fig. 1. Experimental arrangement to identify charged particles. The evacuated chamber is traversed by a magnetic field. The scanned area in the emulsions is shaded in the figure.

Apparatus

Fig. 1 shows the experimental arrangement. An evacuated chamber containing the target is placed in the field of an electromagnet. The gap of the magnet has the dimensions 35 × 12 × 3 cm. The strength of the field is 15000 gauss. The magnet current is obtained from a motor-generator set. The current is regulated by means of a feed-back system giving a constancy in the magnetic field of better than 1 part in 1000. The magnetic field was measured by means of a Hall generator, which had been calibrated against a proton resonance device. The field was mapped and in the region used the maximum deviation was less than 0.3 %. During an experiment the field strength is monitored by the Hall generator.

The emitted particles are recorded by two nuclear emulsions of the size 2″ × 4″ type Ilford C2. The emulsions are placed at an angle of 11.5° to the plane of the chamber. In order to prevent the heat from the magnet from raising the temperature of the chamber, which would cause damage on the emulsions, the chamber is cooled by water. The temperature is continuously measured during the experiments and it never exceeds 20°C.

The targets, consisting of thin foils of various elements, are placed in the chamber as indicated in Fig. 1. The incoming radiation, for example the X-ray beam from a synchrotron, passes through the chamber via a tube, which is closed at both ends by thin aluminum foils.

The chamber is shielded from background radiation by a lead wall. Furthermore the whole magnet is surrounded by boron–paraffin blocks.

Measurements

The nuclear emulsions are developed and scanned in the usual way. For each track entering the emulsion the entrance co-ordinates, the length and the orientation are measured. It is then possible to calculate the trajectory of the particle giving the track. One gets a number of cases depending on the assumption about the type of the particle (if it is a proton, deuteron, etc.). For each case the intersection with the plane of the target is calculated. From the position of the intersections relative to the target position one can find the type of the particle.

The computation of the particle trajectories is very time-consuming if it is performed with desk machines. It is almost a necessity to have access to a high-speed, electronic computer. In the experiments with the apparatus described here the computations were performed on SMIL (University of Lund Digital Computer). A code was set up which directly gives the intersection of the trajectories with the plane of the target. The energy of the particle as well as the angle of emission are also given. The computer automatically rejects all trajectories which hit the walls of the chamber.

Performance

The method described here has been used for an investigation of the charged particles emitted in the photodisintegration of some nuclides. The performance of the apparatus will be illustrated by some results obtained in this work [7].

Fig. 2 shows a plot of the intersection of the trajectory with the plane of the target

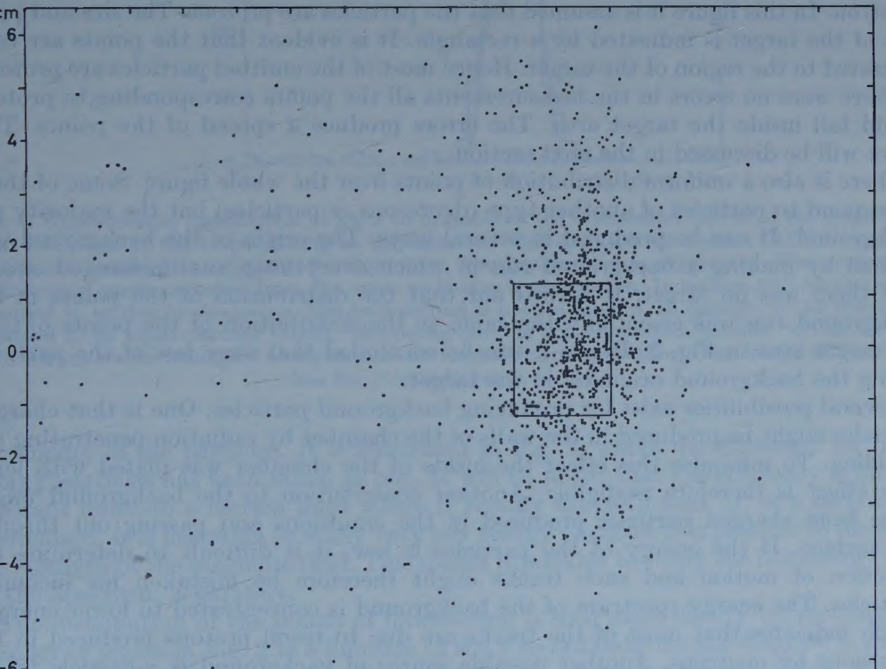

Fig. 2. A plot of the intersection points between the calculated trajectories and the target plane from a cobalt exposure assuming that all the tracks in the emulsions are due to protons. The size and position of the target is indicated by a rectangle.

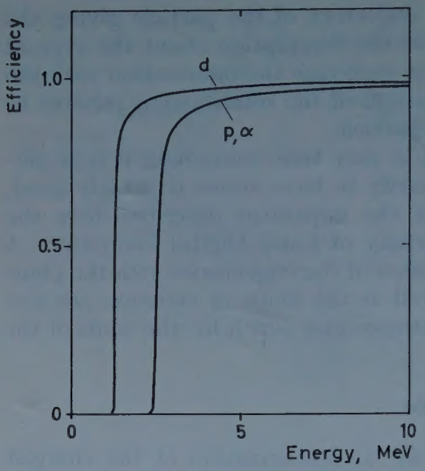

Fig. 3. Efficiency of the apparatus for different kinds of charged particles when the emulsions were scanned in the shaded area of Fig. 1. The efficiency for high energy particles has been taken as one.

(the x_t, z_t plane where the z-axis is parallel with the direction of the magnetic field) when a thin cobalt target is bombarded with 30 MeV bremsstrahlung from a synchrotron. In this figure it is assumed that the particles are protons. The size and position of the target is indicated by a rectangle. It is evident that the points are concentrated to the region of the target. Hence most of the emitted particles are protons. If there were no errors in the measurements all the points corresponding to protons would fall inside the target area. The errors produce a spread of the points. This effect will be discussed in the next section.

There is also a uniform distribution of points over the whole figure. Some of them correspond to particles of another type (deuterons, α-particles) but the majority are background. It can be produced in several ways. The origin of the background was studied by making a background run in which everything was unchanged except that there was no target. It turned out that the distribution of the points in the background run was essentially the same as the distribution of the points outside the target area in Fig. 2. Hence it can be concluded that very few of the particles giving the background originate in the target.

Several possibilities exist for producing background particles. One is that charged particles might be produced in the walls of the chamber by radiation penetrating the shielding. To minimize this effect the inside of the chamber was plated with lead. This effect is therefore negligible. Another contribution to the background might come from charged particles produced in the emulsions and passing out through the surface. If the energy of the particles is low, it is difficult to determine the direction of motion and such tracks might therefore be mistaken for incoming particles. The energy spectrum of the background is concentrated to lower energies which indicates that most of the tracks are due to recoil protons produced in the emulsions by neutrons. Another possible source of background is α-particle tracks in the emulsions. Especially if they are faded, it is difficult to distinguish them from proton tracks. There is finally the possibility of mistakes in measuring the tracks and in calculating the results. A check on a selected number of tracks showed that a small part of the background actually arises in this way.

A question of some importance is how the efficiency of the apparatus varies with

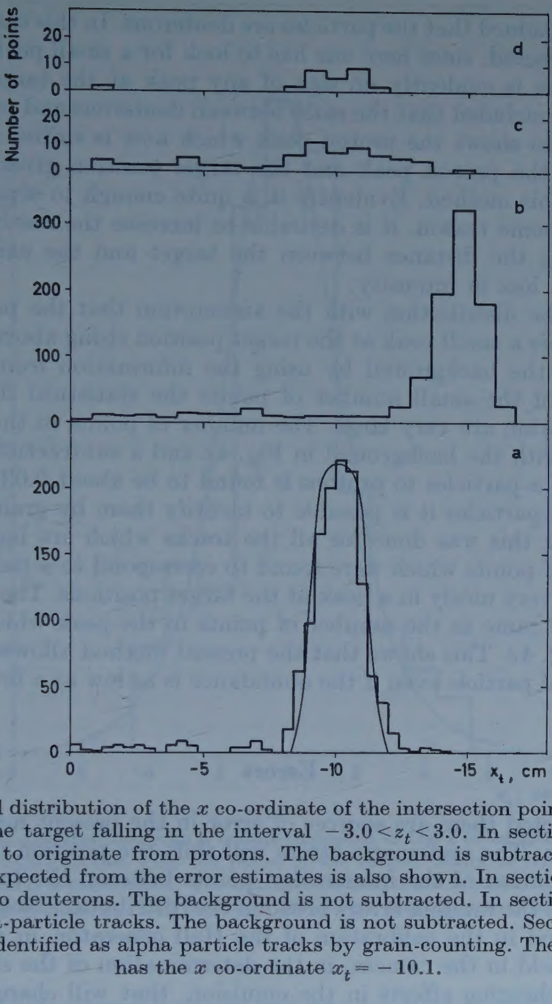

Fig. 4. Experimental distribution of the x co-ordinate of the intersection points of the trajectories with the plane of the target falling in the interval $-3.0 < z_t < 3.0$. In section "a" all measured tracks are assumed to originate from protons. The background is subtracted. The normalized distribution curve expected from the error estimates is also shown. In section "b" all tracks are assumed to be due to deuterons. The background is not subtracted. In section "c" all tracks are assumed to be alpha-particle tracks. The background is not subtracted. Section "d" shows only points from tracks identified as alpha particle tracks by grain-counting. The centre of the target has the x co-ordinate $x_t = -10.1$.

the energy of the particles. It is illustrated in Fig. 3, where the efficiency for high-energy particles has been taken as one. It will be noted that the efficiency is almost constant down to a certain limit where it rapidly drops to zero. If, in a certain investigation, it is desirable to study very low energy particles it is possible to decrease the strength of the magnetic field. This makes it possible to study the low energy part of the spectrum separately.

The distribution of the points of intersection is seen more clearly by plotting the number of points in Fig. 2 as a function of the x co-ordinate. Such a diagram is shown in Fig. 4. All points between the limits $3.0 > z_t > -3.0$ have been included. Fig. 4*a* corresponds to the assumption that the particles are protons. There appears a symmetric peak centered around the position of the target ($x_t = -10.1$). The background has been subtracted by using the distribution obtained in the background run. The remaining points to the left of the peak are partly due to statistical fluctuations in the background and partly due to α-particles.

In Fig. 4*b* it is assumed that the particles are deuterons. In this case the background has not been subtracted, since here one has to look for a small peak above the background level. There is evidently no sign of any peak at the target position. From this figure it was concluded that the ratio between deuterons and protons is less than 1 %. The figure also shows the proton peak which now is shifted to the right. The distance between the proton peak and the target position gives an indication of the resolution of this method. Evidently it is quite enough to separate protons and deuterons. If, for some reason, it is desirable to increase the resolution, this can be done by increasing the distance between the target and the emulsions. However one then suffers a loss in intensity.

Fig. 4*c* shows the distribution with the assumption that the particles are α-particles. There appears a small peak at the target position rising above the background. One can subtract the background by using the information from the background run. On account of the small number of points the statistical fluctuations in the remaining distribution are very large. The number of points in the background run agrees, however, with the background in Fig. 4*c* and a subtraction leaves the small peak. The ratio of α-particles to protons is found to be about 0.03.

In the case of α-particles it is possible to identify them by grain-counting on the tracks. As a check this was done for all the tracks which are included in Fig. 4*c*. The distribution of points which were found to correspond to α-particles is shown in Fig. 4*d*. They fall very nicely in a peak at the target positions. The number of points in this peak is the same as the number of points in the peak which rises above the background in Fig. 4*c*. This shows that the present method allows the identification of a certain kind of particle even if the abundance is as low as a few per cent.

Errors

As will be expected there are sources of error in the present method, both systematic and random. The systematic errors will shift the position of the peak in the co-ordinate distribution of the intersection points between the trajectories and the target plane, while the random errors broaden the distribution. Sources of systematic errors will be found in the calibration of the Hall generator, in non-homogeneities of the magnetic field in the camera, in the determination of the shrinkage factor of the emulsion, in shearing effects in the emulsion, that will change the orientation of the tracks and in the calibration of the microscope ocular scale. Sources of random errors will be found in the horizontal length and dip measurements and in the angle measurements of the track. Small-angle deflections as well as large-angle deflections of the tracks in the emulsion will also cause random errors.

The error in the calibration of the Hall generator is negligible as the calibration points fall very closely on a smooth curve. However, there exists a small random error in the reading of the instruments. This error is of the same size as the error from non-homogeneities in the magnetic field and amounts to 0.3 %.

The shrinkage factor of the emulsion was carefully determined with a sensitive micrometer that needed a force of only 10 gramsforce for the pointer to deviate. The anvil of the micrometer was a spherical surface with a fairly small curvature. A piece of the emulsion plate was glued to a well-polished glass plate. It was evacuated for some days and then rapidly placed on the micrometer table. The thickness of the emulsion plate and the glass plate was measured at different points. The emulsion then

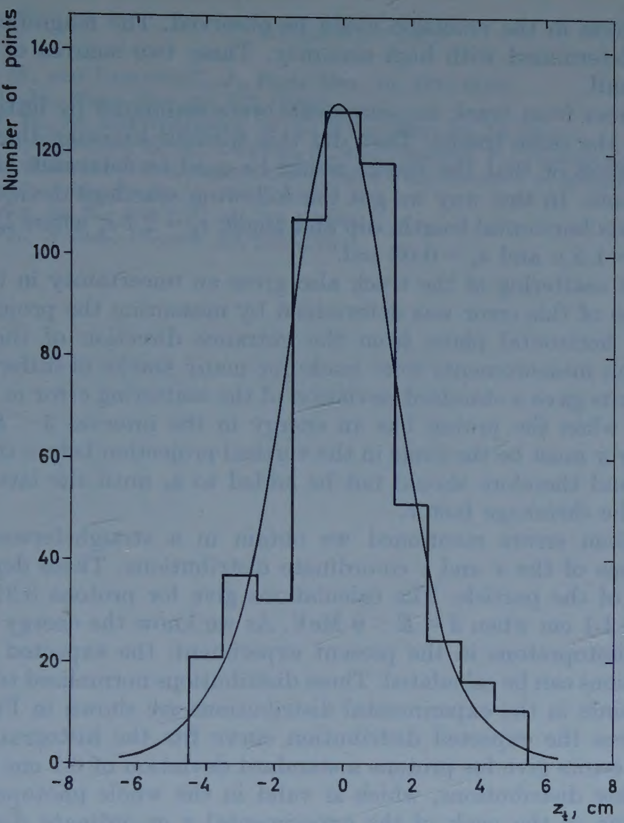

Fig. 5. Experimental distribution from a cobalt exposure of the z co-ordinate of the intersection points of the proton trajectories with the plane of the target falling in the interval $-8.4 > x_t > -11.6$. The background is subtracted. The normalized distribution curve expected from the error estimates is also shown. The centre of the target has the z co-ordinate $z_t = 0.0$.

passed through the developing process and was air-dried in the scanning room that had a constant humidity of 60 %. The thickness of the emulsion plate and the glass plate was measured again at the same points. Finally the emulsion was removed and the thickness of the two glass plates was measured. These three measurements gave the shrinkage factor of the emulsion. Three independent series of measurements were performed giving a mean value of 2.47 ± 0.05. As the micrometer was sensitive and the anvil had only a small curvature giving a large contact area, we feel that the systematic error in the shrinkage factor determination originating from a deformation of the nuclear emulsion by the micrometer anvil is negligible. Fig. 5 shows the distribution of the z co-ordinate of the intersection points between the trajectories and the target plane from the cobalt exposure. The position of the peak in the distribution is sensitive to the shrinkage factor. As the peak falls close to the z co-ordinate of the centre of the target, $z_t = 0.0$, this is a proof of the correctness of the determined shrinkage factor.

No shearing effects in the emulsion could be observed. The magnification of the microscope was determined with high accuracy. These two sources of errors were therefore very small.

The random errors from track measurements were estimated by letting different scanners measure the same tracks. They did this without knowing that the tracks were measured before or that the tracks would be used to determine the accuracy of the measurements. In this way we got the following standard deviations for the three measurements horizontal length, dip and angle: $s_h = 2.7\ l_h$ where l_h is the horizontal length, $s_d = 1.5\ \mu$ and $s_\varphi = 0.03$ rad.

The small-angle scattering of the track also gives an uncertainty in the dip. The standard deviation of this error was determined by measuring the projection of the deflection in the horizontal plane from the entrance direction of the end point of the tracks. Such measurements were made for many tracks of different lengths. These measurements gave a standard deviation of the scattering error in the interval $6.2 < s_s < 20.6\ \mu$, when the proton has an energy in the interval $3 < E_p < 9$ MeV. This scattering error must be the same in the vertical projection before the shrinkage of the emulsion and therefore should not be added to s_d until the latter has been multiplied with the shrinkage factor.

From the random errors mentioned we obtain in a straightforward way the standard deviations of the x and z co-ordinate distributions. These depend on the kind and energy of the particle. The calculations give for protons $0.31 > s_x > 0.20$ cm and $2.5 > s_z > 1.1$ cm when $3 < E < 9$ MeV. As we know the energy distribution of the emitted photoprotons in the present experiment, the expected x and z co-ordinate distributions can be calculated. These distributions normalized to the number of intersection points in the experimental distributions are shown in Figs. 4 and 5. In both the figures the expected distribution curve fits the histogram very well.

The systematic errors give for protons a standard deviation of 0.1 cm for both the x and z co-ordinate distributions, which is valid in the whole photoproton energy range. The position of the peak of the experimental x co-ordinate distribution in Fig. 4*a* has the value $x_t = 10.1$ which should be compared with the x co-ordinate of the centre of the target foil $x_t = 10.1$. The corresponding values for the z co-ordinate distribution in Fig. 5 are $z_t = 0.1$ for the peak and $z_t = 0.0$ for the target centre.

Conclusions

The method described here makes it possible to obtain a complete separation of charged particles. A disadvantage is that the measurements and the computation are rather tedious. The great advantage is that the method can be used for low energy particles and for low intensities. Another advantage is that even a high background of photons and electrons is not disturbing. There does not seem to exist any other method which is suitable under these conditions.

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